A Vacuum Spectrograph for the Infra-Red*

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A description is given of a 1-meter focus vacuum grating spectrometer for the infra-red which is distinguished by its versatility and compactness of design. The vacuum container is tubular in form and all optical parts are mounted on a carriage which is readily retractable from the case for adjustment. A novel feature is the use of a sine screw drive which gives a linear wave-length scale. A representative spectrum tracing is given.

CONSTRUCTION of a vacuum grating spectrograph for the infra-red was completed in this laboratory just prior to the recent war. Unfortunately, use of the equipment was considerably delayed by war activities and it has never been described. However, since the instrument has some novel features and is distinguished by its compactness and versatility, a description at this time may be of some interest.

The advantage to be gained by the use of vacuum spectrographs for infra-red investigations was obvious long before the first infra-red vacuum instrument was constructed by one of us twenty-one years ago.[1] It is consequently remarkable that of the numerous instruments constructed since that time such a small percentage have been made evacuable. Attempts to eliminate completely the interference of water vapor and carbon dioxide by the use of drying agents, or by flushing the spectrometer case with dry nitrogen, generally end in complete frustration. The double beam construction, at present so popular, has indeed done much to reduce the inconveniences of the contamination, but even in principle cannot entirely eliminate its effect if the spectrometer has finite resolving power.

Many of the vacuum instruments which have been constructed have been very bulky and sometimes excessively expensive. In the case of the instruments of the size so widely used today for analytical purposes this seems unnecessary, if more thought were spent in design. The larger instrument presents greater problems if all parts are to be made readily accessible for adjustment. The most obvious solution is to tailor a case to fit a preconceived instrument. This, however, because of its awkward shape may require massive construction for strength, and may present problems in maintaining a vacuum.

The logical vacuum container combining strength with moderate weight appears to be tubular, and certainly in many cases an instrument can be designed to fit within such a housing. If all parts are to be readily accessible for adjustment, however, it is highly desirable either that the container be removable from the stationary spectrograph, or that the latter be readily removable as a whole from its container. The former alternative has been employed,[2] and has the obvious advantage that internal and external optical paths may be adjusted as a whole. It is, however, likely to require relatively massive and expensive construction. The latter arrangement was consequently chosen by us, and in practice has been found to be very convenient. Though the instrument to be described was designed several years ago and has only recently been put into operation we have found no radical alteration necessary, though the flexible construction has permitted the adoption of several recent improvements.

As shown in Fig. 1 all parts of the spectrometer proper are mounted on a carriage, which is readily rolled from its vacuum case onto an auxiliary table for adjustment. The carriage is a rectangular "cage" of which the sides consist of two 8-inch expanded *I* beams, a material

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[1] R. M. Badger, Proc. Nat. Acad. Sci. **13**, 408 (1927); R. M. Badger and C. H. Cartwright, Phys. Rev. **33**, 692 (1929).

[2] Martin, Fischer, Mandel, and Nusbaum, J. Opt. Soc. Am. **37**, 923 (1947).

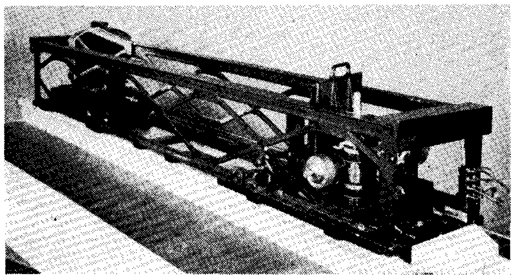

FIG. 1. Full view of the spectrometer carriage. The grating table and sine screw driving mechanism appear in the foreground and the off-axis mirror at the rear.

known as Kalman Stud and manufactured by the Bethlehem Steel Corporation. This material offers great advantage for constructions of this sort. The open work, truss-like structure, though relatively light, provides adequate rigidity and at the same time accessibility of all enclosed mechanism. The *I* beams are tied together by rigid rectangular frames at each end, and by appropriately spaced cross bars welded to their lower surfaces. The under surfaces of these bars, to which the mirror support and grating table support are bolted, were machined to lie all in the same plane, which serves as a reference plane for all adjustments.

To prevent possible warping during transport the spectrometer carriage is provided with three-point support. At one end of the carriage a rather massive two-wheeled truck supports the slit mechanism, the grating table, and the mechanism for rotating the table. One wheel of the truck has a *V* groove and rides on a rail with semicircular profile. The other wheel rides on a flat rail. The third support is located beneath the center of the mirror table. A ball and socket joint is carried by a three-wheeled bogie truck, the two guiding wheels of which have V grooves.

As shown in Fig. 2, an auxiliary table with tracks is provided for carrying the spectrometer when it is withdrawn from its case for adjustment. The table is furnished with large castors which make it readily movable. These can be retracted by a lever arrangement and the table allowed to rest on rigid feet which permit appropriate adjustment of height.

The spectrograph is of the Littrow type. The off-axis parabolic mirror is 100 cm in focus with axis passing through the center of its lower edge. It was intended to cover a 5-×7-inch grating and its usable area is slightly in excess of this size.

The spectrograph slit is located on the side of the carriage, and incoming and outgoing beams are diverted through 90° by a narrow mirror, $\frac{15}{16}\times 2\frac{1}{8}$ inches, which is centered on the optical axis, and obscures a negligible portion of the grating. The slit is $1\frac{11}{16}$ inches long and is of bilateral construction. In present use the entering and emerging beams pass, respectively, through upper and lower halves of the same slit. This arrangement necessitates some provision to prevent overlapping of the two beams exterior to the spectrograph slit. This is taken care of by two fluorite field lenses mounted at the slit. These are located off center in such a fashion that in the vertical plane a sufficient angle is made by the two beams to keep them well separated as they diverge.

The grating table is carried by a cone bearing. To prevent binding the vertical thrust is taken by an adjustable ball and plane bearing. The grating table is rotated by a sine screw arrangement which has the advantage of giving a linear wave-length scale, when properly adjusted. A five-inch arm projecting from the table terminates in a hardened ball, $\frac{1}{2}$ inch in diameter. By an appropriate spring this ball is kept in contact with a hardened steel optical flat. If this flat is moved parallel to itself the translation is proportional to the sine of the angle of rotation of the grating table, provided that in the zero position a line connecting the center of the ball and the axis of rotation is parallel to the surface of the flat. The optical flat is mounted on a massive nut running on a precision screw having 50 threads per inch. Rotation of the nut is prevented by a weighted arm which rides on a

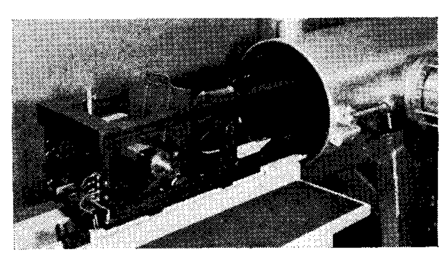

FIG. 2. Spectrometer carriage emerging from the vacuum case. The slit is obscured by the field lenses to the right of the grating holder.

plane, horizontal bearing surface parallel to the axis of the screw.

The screw is rotated by a worm wheel and worm with quadruple thread, which give a twelvefold reduction. The worm shaft is vertical and its upper end can be connected to a drive shaft passing through the spectrometer case by means of a retractable coupling. Below the worm the shaft is connected to a Veeder counter visible through a window in one of the closure plates of the case. A cam is also provided which actuates a micro switch to provide reference "pips" on the recorded spectra. The drive shaft passing through the spectrometer case is made tight with an "O" ring seal which does not leak even at high speeds of rotation.

In practice it has been found that the sine screw mechanism gives a slight deviation from a linear wave-length scale. This deviation seems to be symmetrical about the zero position and decreases with increasing wave-length. It may be due to slight curvature of the optical "flat" or lack of roundness of the ball. It could doubtless be easily eliminated, but is not large enough to be bothersome.

Each grating is supplied with a separate holder having three ball feet which rest in hardened V grooves on the grating table. Adjustments are provided for leveling, and for a rotation of the grating to permit adjustment of the zero.

The vacuum container for the spectrograph consists of a section of wrought steel tubing $64\frac{5}{8}$ inches long, $14\frac{1}{8}$ inches in internal diameter, and about $\frac{7}{16}$ inch thick. It is supported on a rigid steel framework with its center 39 inches above the floor. The ends of the casing are closed by two removable circular steel plates $\frac{3}{4}$ inch in thickness. Appropriate side tubes were welded on for vacuum connections and to admit shafts for actuating the drive and slit mechanisms. Facing the spectrometer slit a flanged opening, $6\frac{1}{2}$ inches in diameter is provided for the attachment of a variety of external apparatus. In Fig. 3 an auxiliary housing is shown in place. This contains the mounting and mirror for a Beckman thermocouple and a mirror and lens for diverting the entrant beam and focusing an image of the source upon the slit. The entrant beam normally comes from a direction parallel with the spectrometer axis and enters the auxiliary housing through a vacuum tight window or collimating lens in its side.

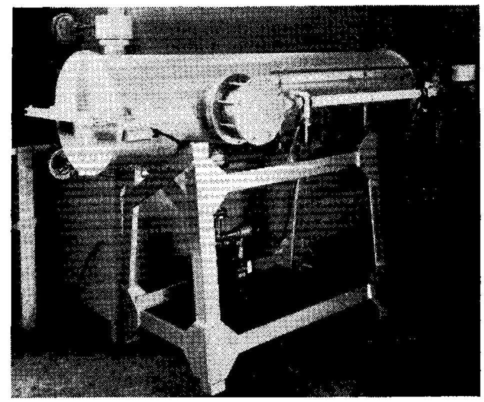

FIG. 3. Side view of vacuum spectrometer showing auxiliary thermocouple housing and some accessory equipment in the external optical path.

Space is provided in the auxiliary chamber for a foreprism in Wadsworth mounting, though recent developments in filters may make this provision unnecessary.

The spectrograph case together with the attached thermocouple housing can be brought down to a pressure of 0.1 mm in 30 minutes with a Welch Duo-Seal 1405 pump.

A rigid rack secured to the side of the spectrometer case permits the attachment of a variety of auxiliary equipment, including sources, absorption tubes, polarizers, photometers, etc. Great flexibility in the choice of arrangements external to the spectrometer was provided for, and has been found useful, since investigations have so far been made on gases, liquids, and solids. On occasion small portions of the external optical path may be in air, but enclosure of these in short sections of tubing containing drying agents has been found adequate to eliminate water absorption out to 3μ.

The spectrometer is at present provided with replica gratings kindly furnished by Professor R. W. Wood. These gratings have 7500 and 4500 lines per inch, respectively, and are very brilliant. However, with the narrow slit widths made possible by the new and sensitive detectors it is quite evident that somewhat more perfect gratings must be obtained to achieve the limit of practicable resolution. A knife-edge test shows that our present replicas have both large-scale

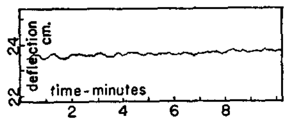

FIG. 4. Recorder trace showing over-all noise registered at 2μ under average working conditions. Detector: lead sulfide cell; grating: replica with 7500 lines/in., first order; slit width: $\sim$0.08 mm; source: 500-watt, 120-volt tungsten projection lamp run at 90 volts. External optical path included absorption cell and filter with short wave cut-off at about 1.1μ.

imperfections, which can be blocked out, and very local variations in grating spacing about which nothing can be done. Presumably these are inherent in the method by which the replicas were produced.

In the neighborhood of 1.9μ, lines in the water vapor spectrum having separations slightly in excess of 1 cm^{-1} are definitely resolved, using the grating with 7500 lines per inch in the first order, and a slit width of approximately 0.08 mm. A considerably narrower slit width is practicable from the standpoint of intensity and would be justified by the optics of the instrument, exclusive of the grating. However, a narrower slit does not effect any improvement in resolving power for the reason mentioned.

The spectrograph has been provided with a vacuum thermocouple which will be operated with an interrupted light beam, but work so far has been done only with the lead sulfide cell used in conjunction with a tuned amplifier with variable band pass. Rectification is accomplished in the last stage of the amplifier and the output is recorded on a Brown high speed recorder.

In the investigation of absorption spectra the source employed out to about 2.8μ is a 500-watt tungsten projection lamp designed for 120 volts, but usually run at about 90 volts. The light source is interrupted at 720 cycles by a sector shutter 19 cm in diameter having 12 slots. This is rotated by a synchronous motor running at 3600 r.p.m. It is not usually convenient for us to locate the sector precisely at a focus and it was found that the use of the sector mentioned effected a 60 percent increase in signal strength over that obtained with one having narrower slots and running at 1800 r.p.m.

In Fig. 4 is shown a trace taken under average working conditions, which gives some indication of the stability of the amplifier and of the magnitude and character of the over-all "noise" registered by the recorder. No special pains were taken to secure optimum conditions. Under the conditions specified the noise contributed by the lead sulfide cell is inconsiderable in comparison with disturbances of rather long period attributable to external sources. The periodic fluctuations of about 2 mm in amplitude shown at one end of the trace may possibly be due to variations in the speed of the sector shutter caused by drifts in the frequency of the 60-cycle supply. The supply is of very constant frequency on the average, but at certain times of day it drifts sufficiently that the band width passed by the

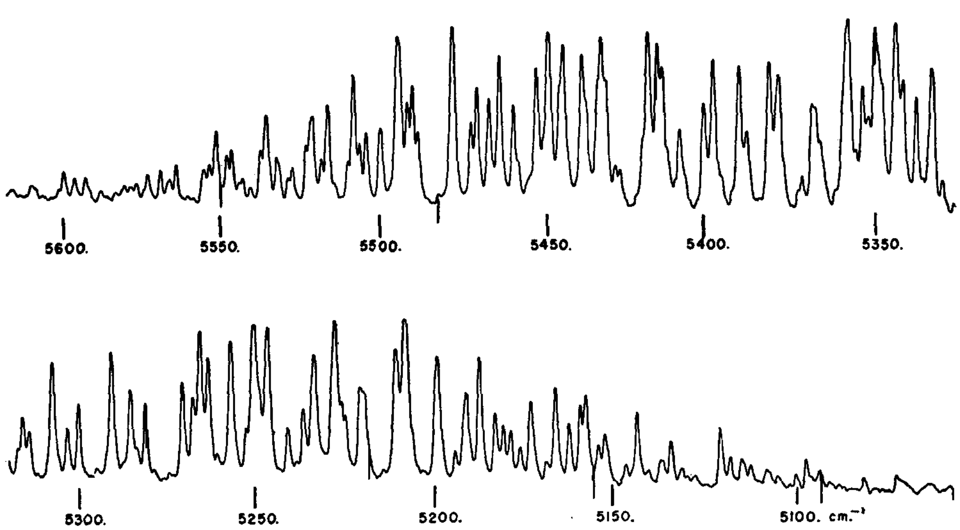

FIG. 5. Trace of the water vapor spectrum at 1.9μ obtained with lead sulfide cell.

amplifier cannot be made as narrow as may be desirable when it is necessary to work with high gain. The stability of our amplifier would appear to warrant a more constant speed drive for the sector.

Our investigations have so far been confined to the region below 2.8μ, where the lead sulfide detector has adequate sensitivity, and no special precautions have been necessary to improve the signal to noise ratio other than to choose a cell for which this ratio is large, though the sensitivity is somewhat less than with other cells. Considerable improvement could no doubt be obtained by more careful selection of the polarizing voltage, by moderate cooling of the cell, and by more careful adjustment of a sharper and smaller image on the sensitive surface of the cell.

The spectrograph has been calibrated with argon lines in the first and second orders. The argon arc gives numerous sharp lines very satisfactory for calibration purposes in the near infra-red. Use of the mercury lines in higher orders has been attempted but the low sensitivity of the lead sulfide cell in the visible makes necessary the use of a rather hot and high pressure arc such as the AH-4 lamp. This appears to give broad, asymmetric lines rather unsuitable for calibration purposes.

Investigations have so far been made on solid films of cellulose and on the vapors of hydrogen peroxide, hydrogen persulfide, hydrogen sulfide, water, and heavy water, which will be published in detail in the near future. Particular attention is being given to the accuracy of measurement of the water lines in the expectation that they may subsequently serve as standards. A representative trace of the water spectrum at 1.9μ is given in Fig. 5, which at both extremities shows a number of water lines which, we believe, have not previously been reported.

In conclusion we wish to acknowledge the many invaluable suggestions given during the design of the spectrograph by Dr. J. H. Sturdivant of this Institute.

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The Electron Multiplier as a Counter for 10-Kev Protons

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Electron multipliers similar to the type described by J. S. Allen are being used as counters for low energy protons. Multipliers with electrodes made from soft beryllium copper count protons in the energy range 5 kev to 10 kev with an efficiency between 80 percent and 100 percent. Efficiencies of about 100 percent have been obtained with a radioactive alpha-source and about 0.2 percent with a RdTh gamma-source.

INTRODUCTION

An attempt is being made to detect the protons resulting from the radioactive decay of the neutron by a method similar to that of A. H. Snell and L. C. Miller[1] of the Clinton National Laboratories. A collimated beam of neutrons from the Chalk River heavy water pile is passed between two electrodes in an evacuated chamber so that the electric field collects any protons resulting from the disintegrating neutrons and accelerates them out of the neutron beam. In order to detect these low energy protons a counter is required which does not depend on gas ionization for its operation and therefore does not require a window to separate it from the vacuum. The electron multiplier satisfies both these conditions and was therefore tested for efficiency when counting 10-kev protons. J. S. Allen[2] and Z. Bay[3] have both obtained 100 percent efficiency when counting alpha-particles and the former has

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[2] J. S. Allen, Rev. Sci. Inst. **18**, 739 (1947).

[3] Z. Bay, Rev. Sci. Inst. **12**, 127 (1941).